Booster Cogging

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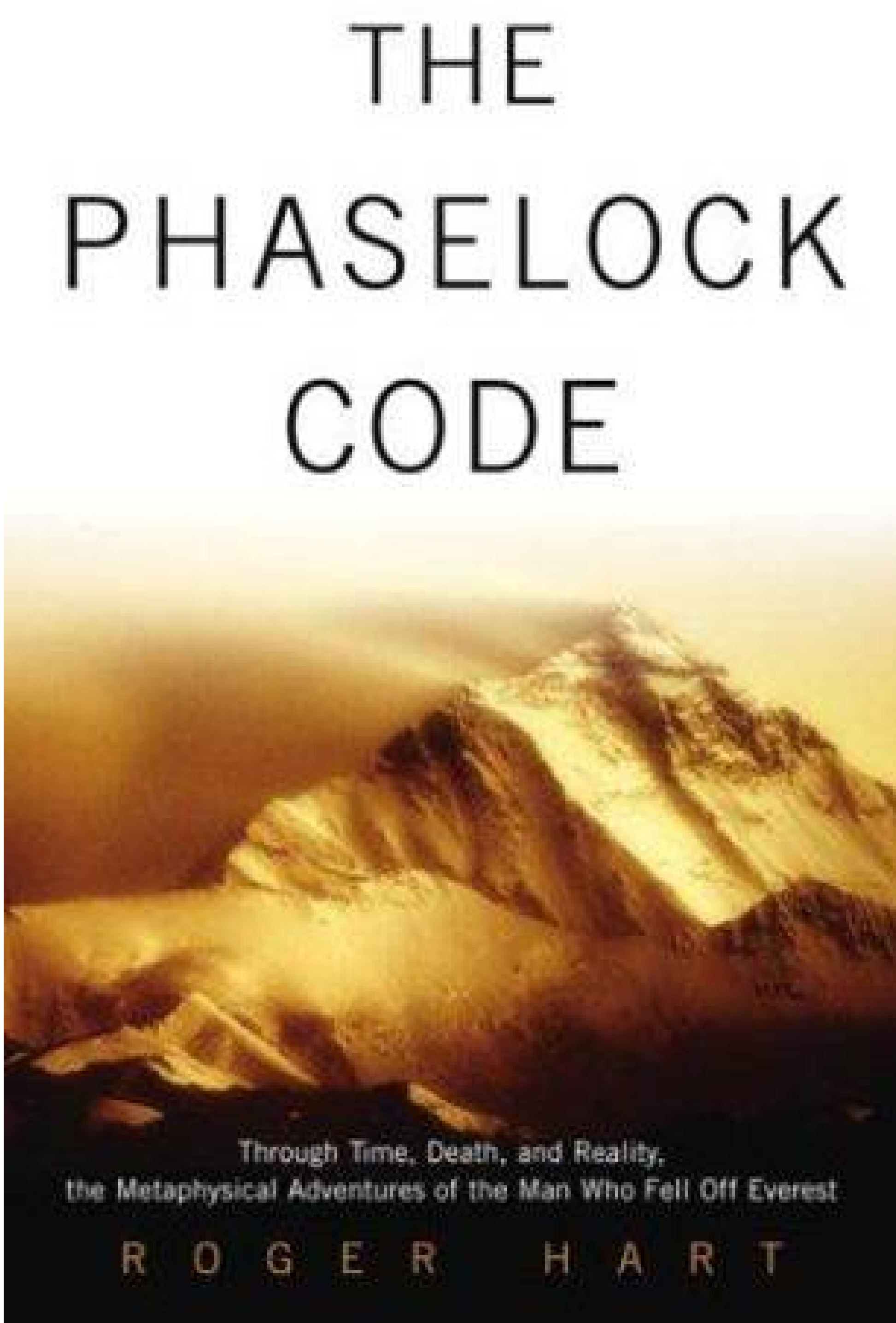
Cogging

- Defined: adjusting the revolution frequency of bunched beam in a synchrotron to correspond to some external frequency

- Examples:
  - Centering collisions in an IR
    - e.g. Tevatron, RHIC
  - RF synchronous transfer between rings
    - Phaselock
  - Synchronization with external beam
    - Booster Cogging

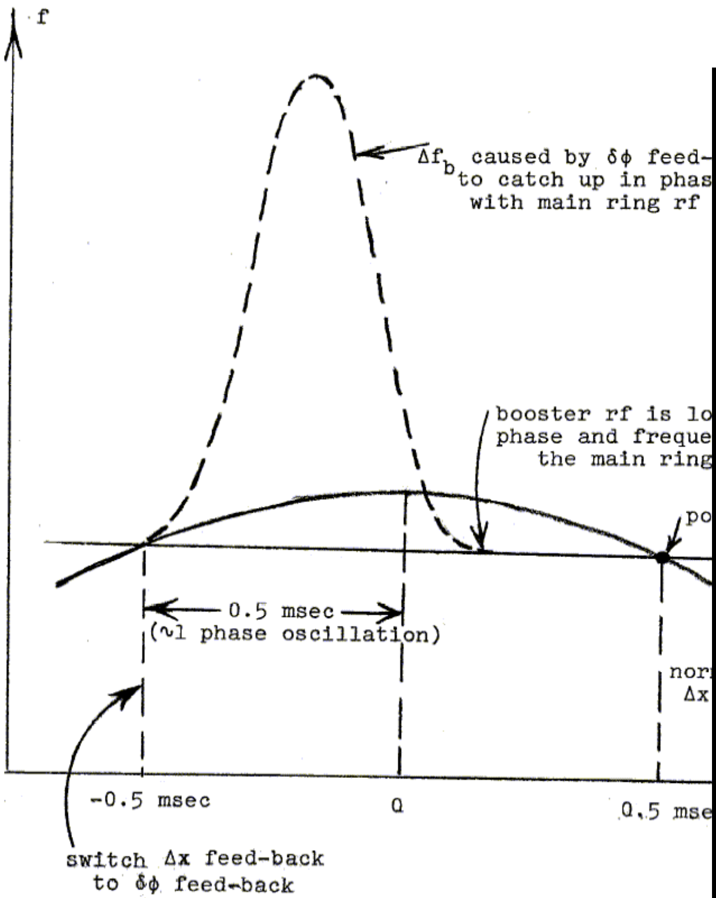
“***Phaselock*** refers to experiments on the interconnectedness of the universe, where changes in one part, create instantaneous changes in the rest of the universe.”

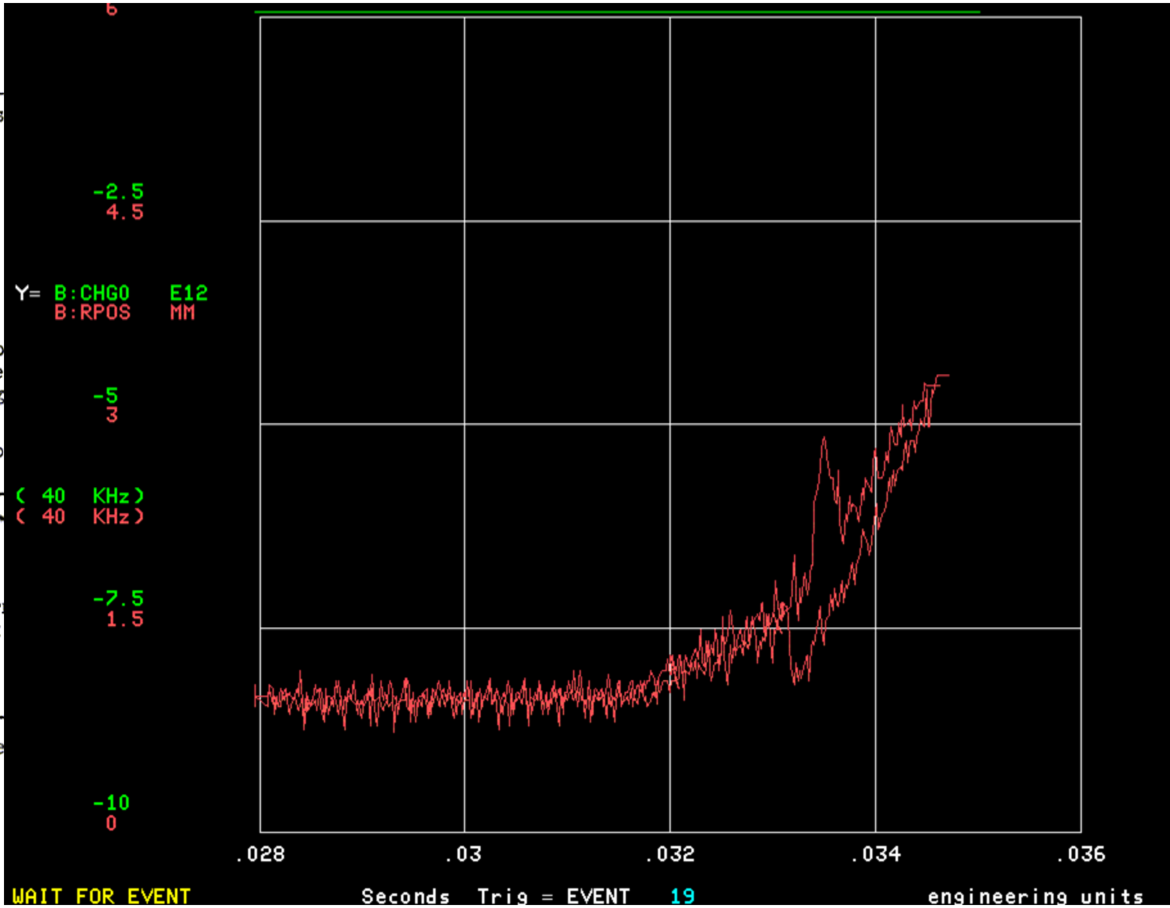


Example: Booster Phaselock

- Match $f_B = f_{MI}$, $\phi_B = \phi_{MI}$
- Control beam's radial position

$$f_B(r) = \frac{hv(r)}{C(r)}$$

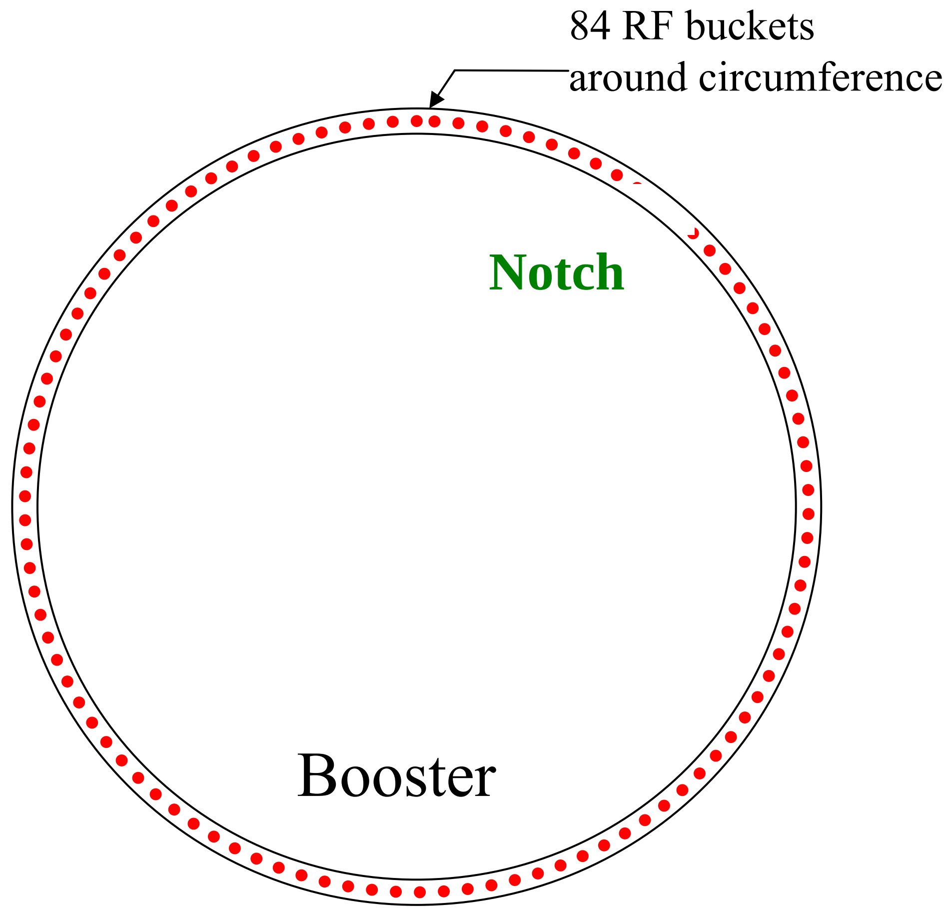




L. C. Teng, FERMILAB-TM-0281

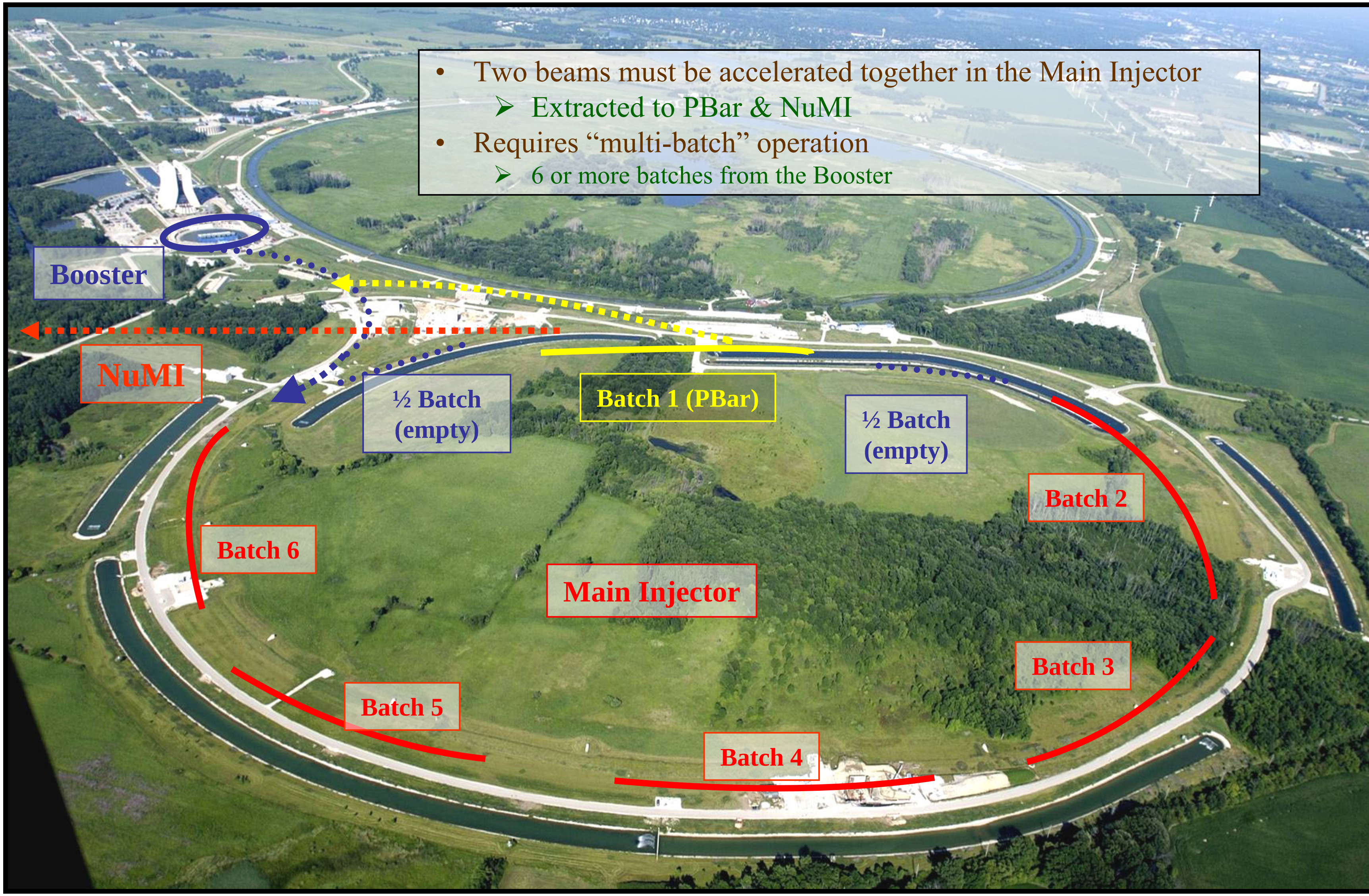
Need for a Notch

- Extraction kicker has risetime of ~ 40 ns
  - Only ~ 10 ns between bunches
- Beam lost at 8 GeV during extraction
- Instead, beam is removed at 400 MeV
  - Reduces energy lost 20x
- Notch implemented for start of Run II and MiniBooNE
  - Reduces extraction loss 10x
- With a single batch, Booster determines beam position in the MI

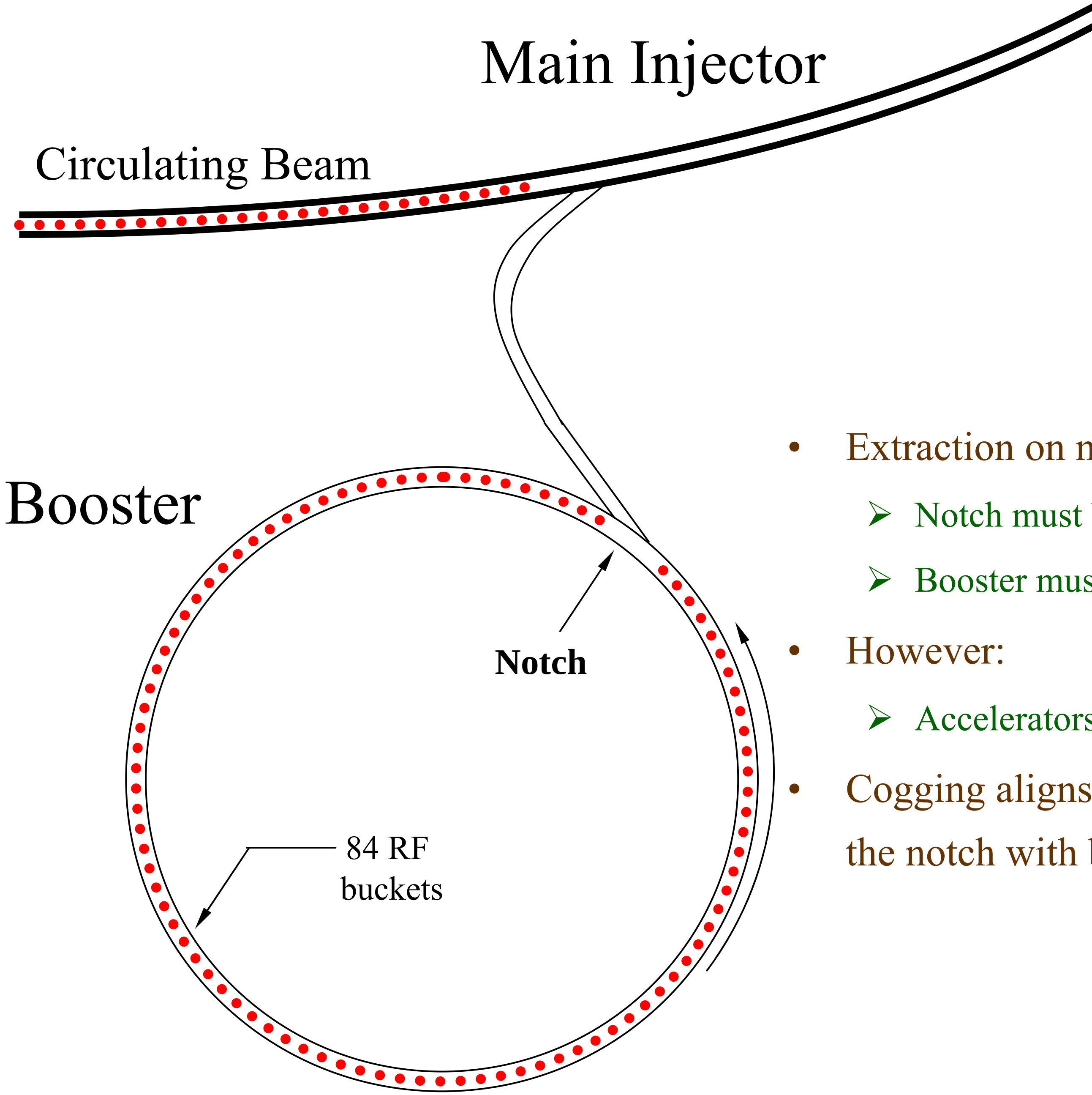


Multi-Batch Operation

- Two beams must be accelerated together in the Main Injector
  - Extracted to PBar & NuMI
- Requires "multi-batch" operation
  - 6 or more batches from the Booster



Booster Cogging

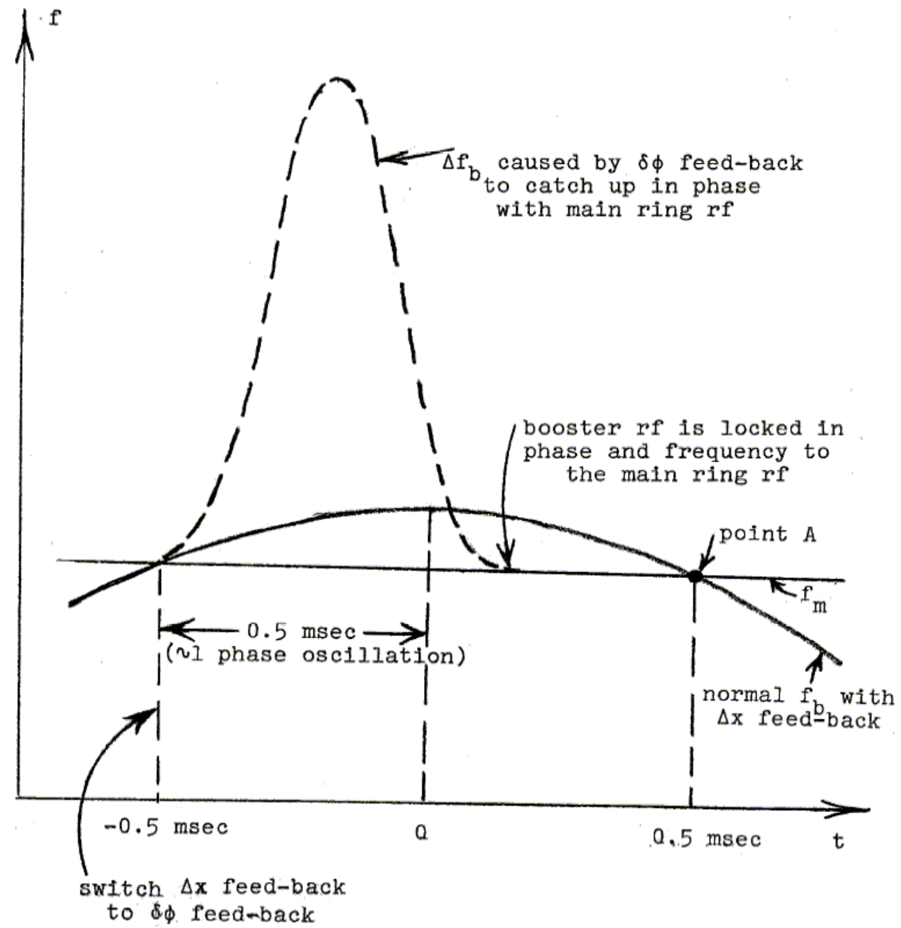


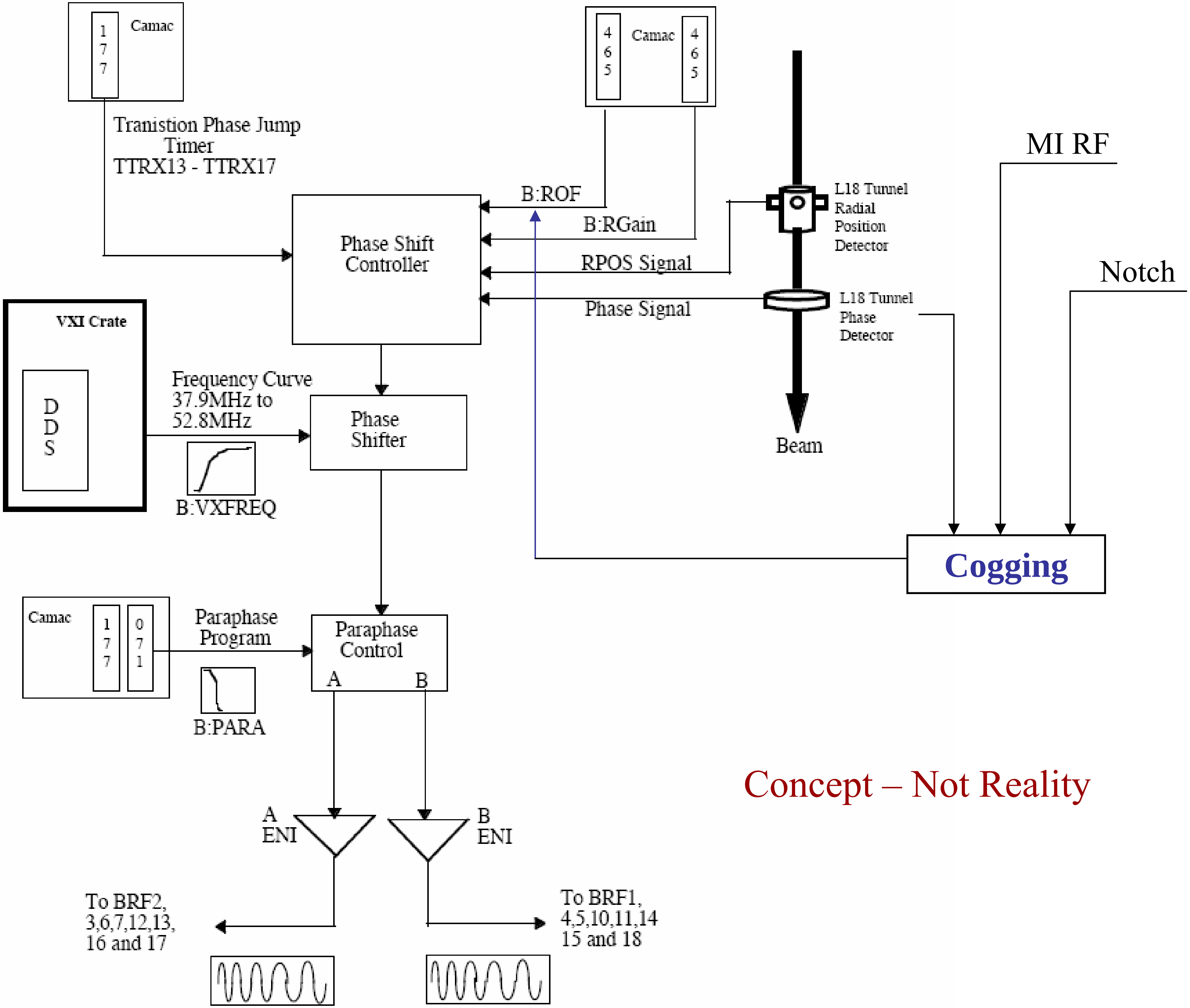
- Extraction on notch
  - Notch must be coincident with kicker pulse
  - Booster must be aligned with MI beam
- However:
  - Accelerators are not synchronized
- Cogging aligns the azimuthal position of the notch with beam in the MI

Do it like phaselock?

- Revolution frequency is 1/84th of RF frequency
  - ➢ 84x the distance to be moved
  - ➢ Needs longer time or larger bump
- Booster has no flattop
- Bump can only be slightly larger

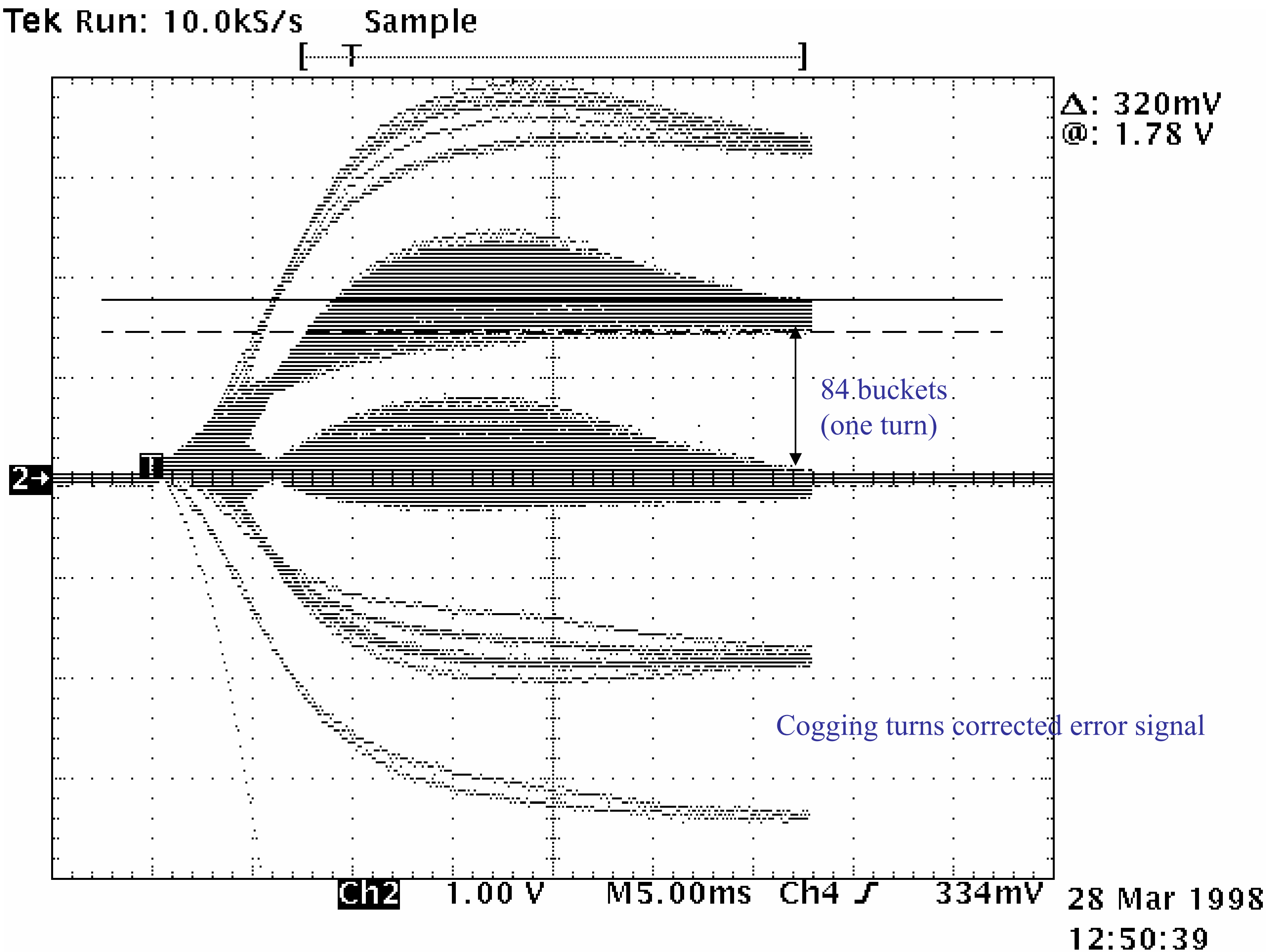
⇒Need to cog during acceleration





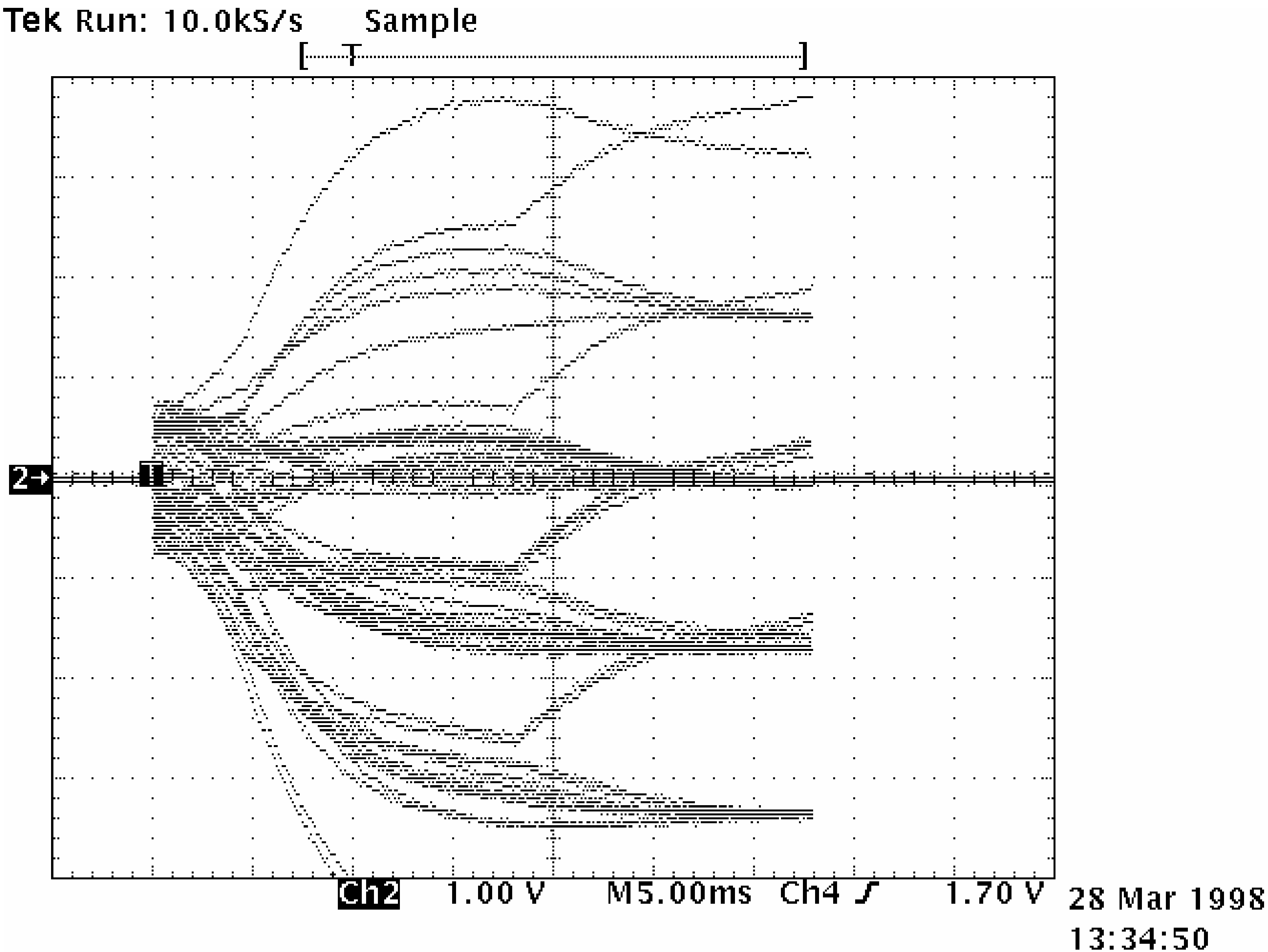
Camac
177
Camac
465
465
Tranistion Phase Jump Timer TTRX13 - TTRX17
B:ROF
B:RGain
RPOS Signal
Phase Signal
Phase Shift Controller
L18 Tunnel Radial Position Detector
L18 Tunnel Phase Detector
MI RF
Notch
Beam
VXI Crate
DDS
Frequency Curve 37.9MHz to 52.8MHz
Phase Shifter
B:VXFREQ
Cogging
Camac
177
071
Paraphase Program
Paraphase Control
A
B
B:PARA
A ENI
B ENI
To BRF2, 3,6,7,12,13, 16 and 17
To BRF1, 4,5,10,11,14 15 and 18
Concept – Not Reality

Cogging Proof of Principle



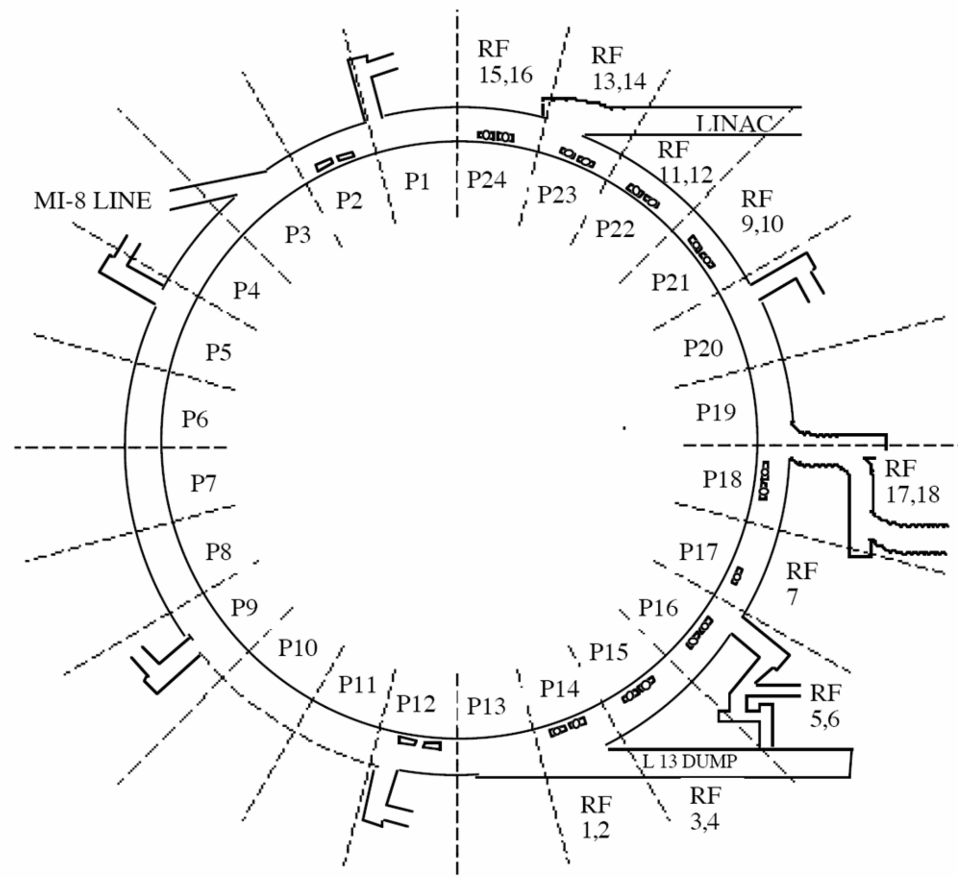
Pellico & Webber

Too Much Feedback



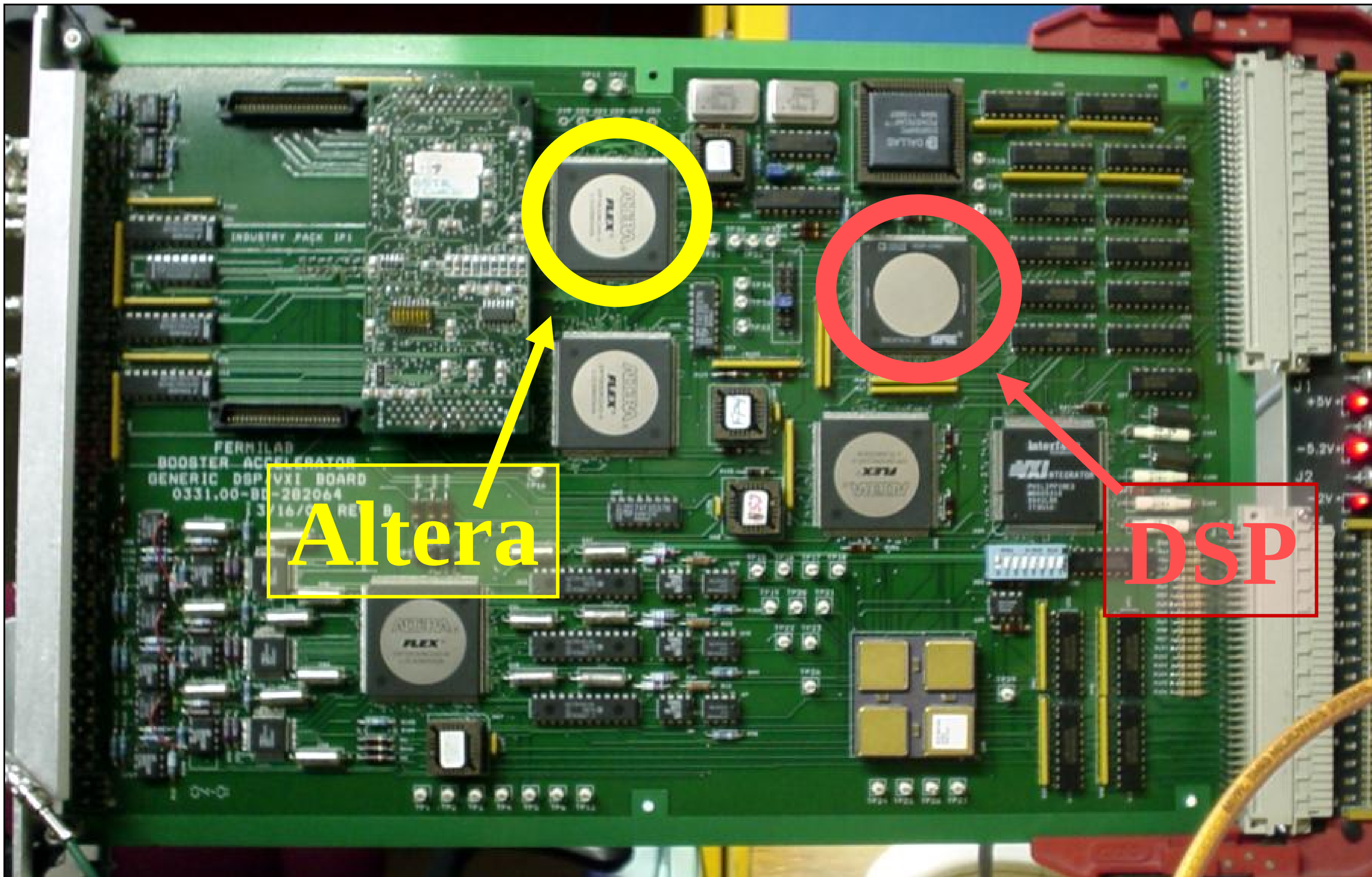
The Cogging System

- Controls:
  - Booster Radial Position
  - Notching
  - Extraction
- MI LLRF constraints
  - Frequency maintained
  - Marker maintained
  - Takes resets from the Booster
- GMPS feedforward
- Beam Information
  - MDAT & Booster Beam Gate
- Triggering
  - BDOT signal
  - TCLK timing



Cogging Electronics

- Use the “Generic” Booster Board
  - Also for GMPS, BLMs, etc.
- Digital and analog inputs/outputs
- Altera FPGA for fast counting
- DSP for calculations



Measurements

- Monitor Notch position throughout the cycle
- Use Main Injector RF as a standard clock
- Booster RF frequency varies with energy
  - 38 → 53 MHz
- Start counting on Main Injector revolution marker (every 11 μs)
- Stop Counting on Booster revolution marker (every 1.6-2.2 μs)
- Makes a table of positions (tripplan)

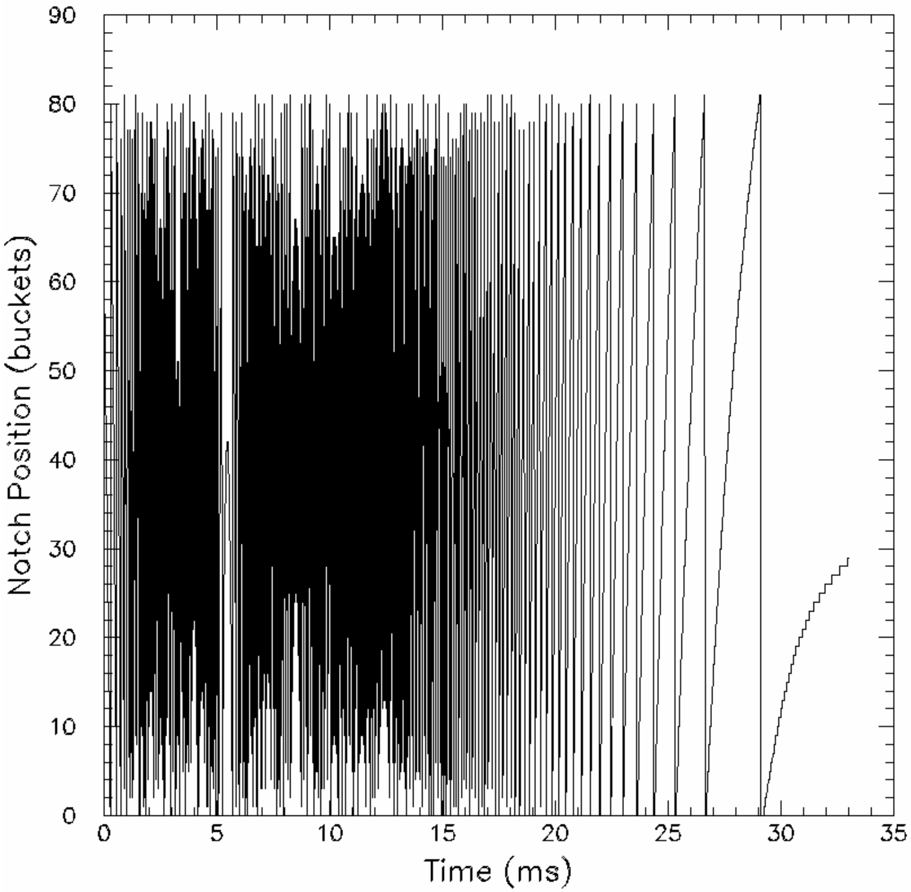
Booster RF

Booster Revolution Marker (Notch)

Main Injector Revolution Marker

Following the Notch

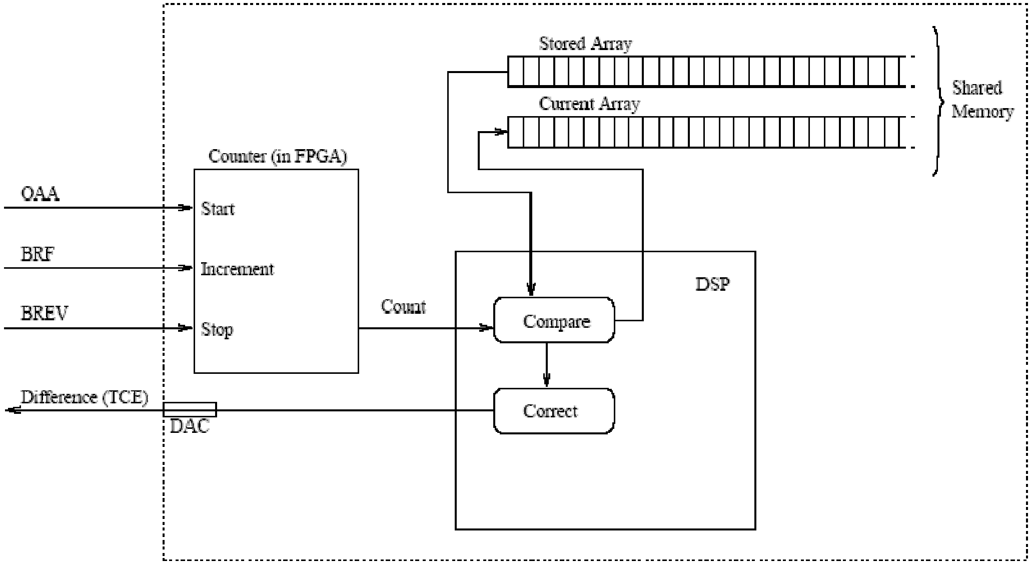
Raw position



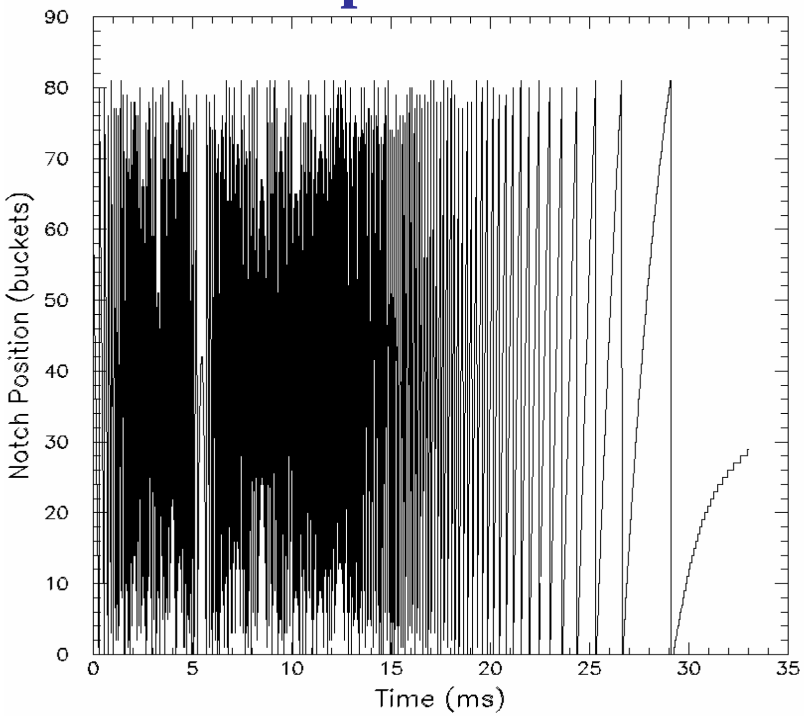
- RF buckets slip at a rate $f_{MI} - f_B \leq 15$ MHz
  - Notch wraps around the Booster many times
- Extraction with one batch
  - Count RF buckets to make a marker
  - Extract on marker
  - Reset Main Injector
- With several batches
  - Clean extraction is possible if total slippage is exactly the same cycle-to-cycle
  - Requires 1 in 1,000,000 consistency…

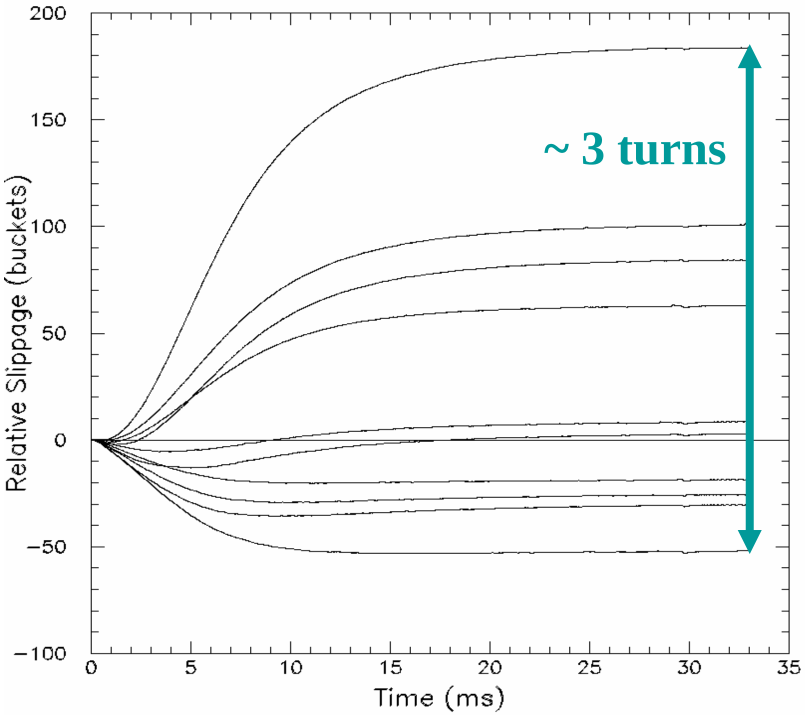
Relative Slippage

- In software, we calculate the relative slippage cycle-to cycle
  - Use a previous cycle as a baseline



Raw position ⇔ **Relative to baseline**





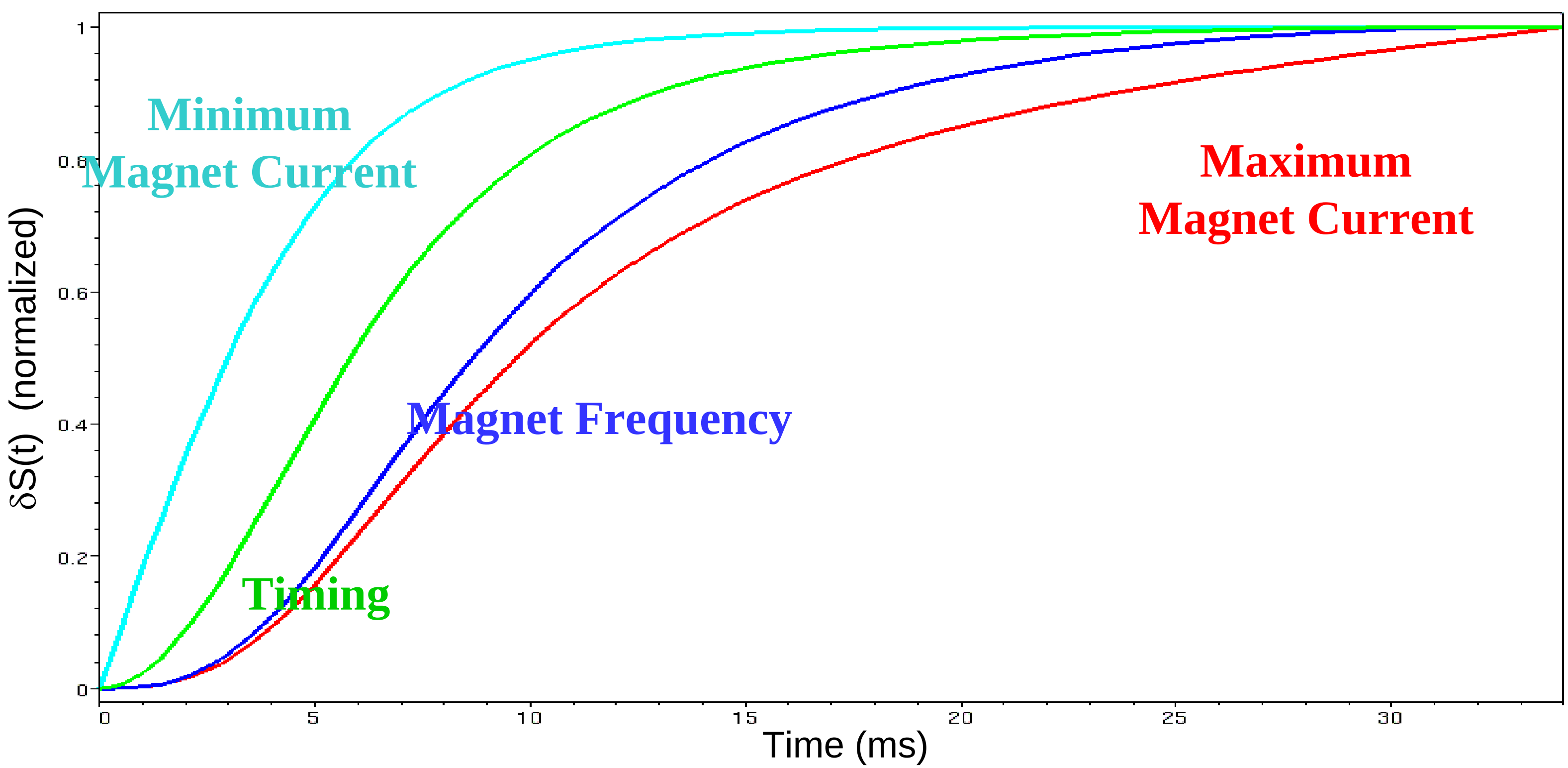
Sources of Slippage

- Any perturbation to RF will cause slippage

$$\text{Slippage}(t) = \int_0^t dt' \, \Delta f_{RF}(t')$$

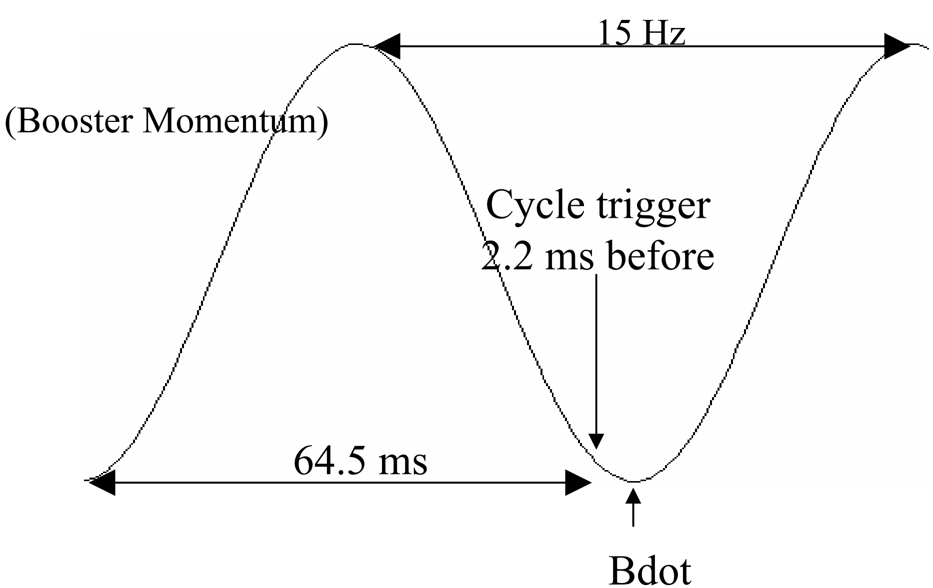
- Over 33 ms Δf = 30 Hz gives 1 bucket slippage
- f = 37 – 53 MHZ $\rightarrow$ part per million problem

- Several possible errors shown below:
  - Timing: 1 μs $\Rightarrow$ 15 bucket slip
  - Magnet Frequency: 1 mHz $\Rightarrow$ 6 bucket slip
  - Minimum Magnet current (δp_i): 1/10,000 $\Rightarrow$ 10 bucket slip
  - Maximum Magnet current (δp_e): 1/10,000 $\Rightarrow$ 7 bucket slip



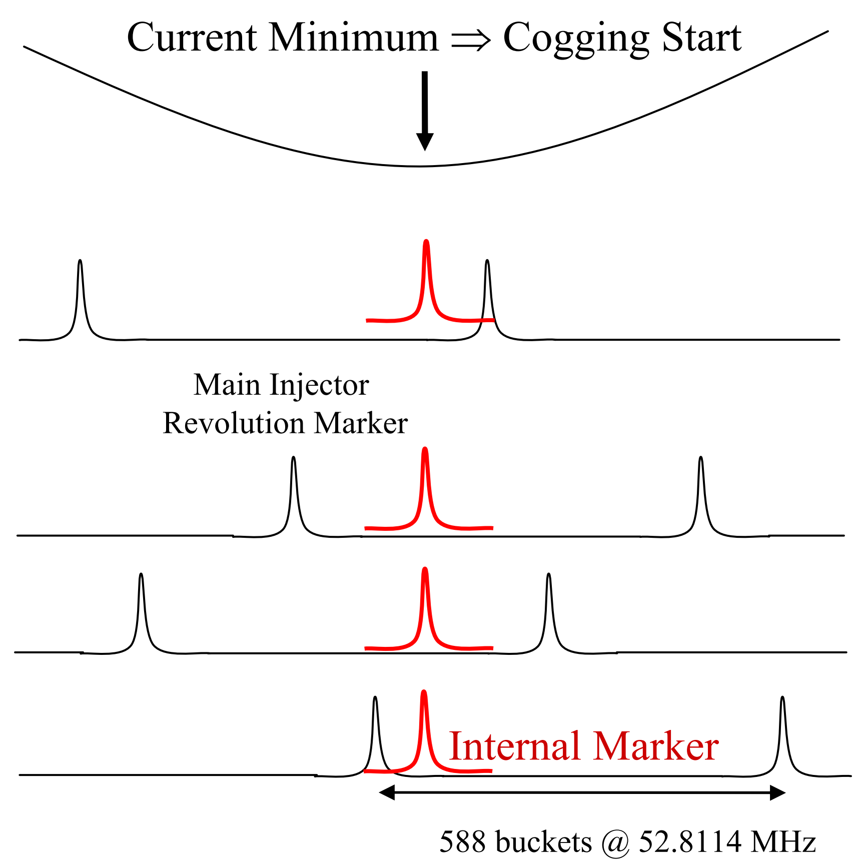
Timing Errors

- TCLK trigger is predicted from the Bdot of the previous cycles
  - Needs to occur few ms before the minimum
- Small variation in 15 Hz frequency can lead to μs errors



Fix: trigger data-taking on magnet minimum instead of clock

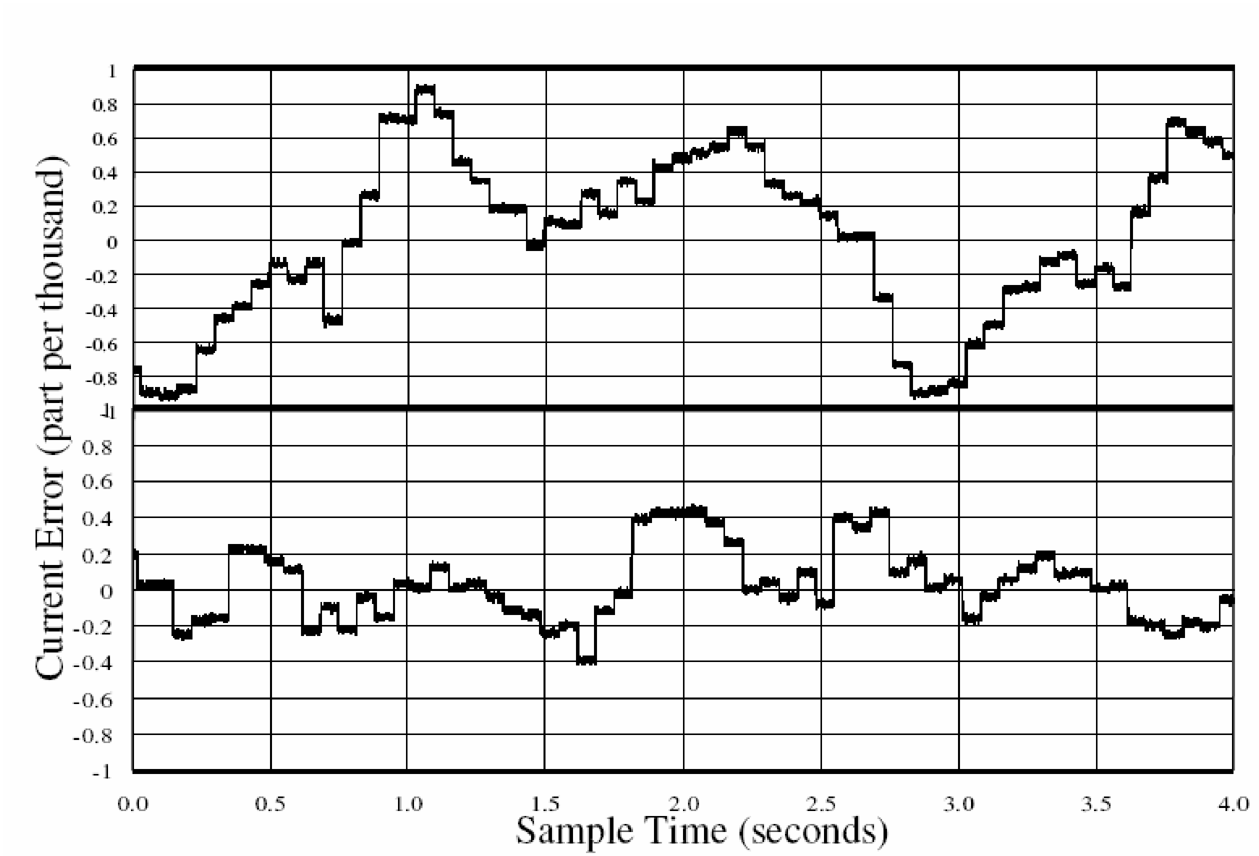
- MI markers come at arbitrary times w.r.t. trigger
- Leads to a timing error of as much as 11 μs
- Solution ⇒ Generate an internal marker synchronized to the cogging start



GMPS Regulation

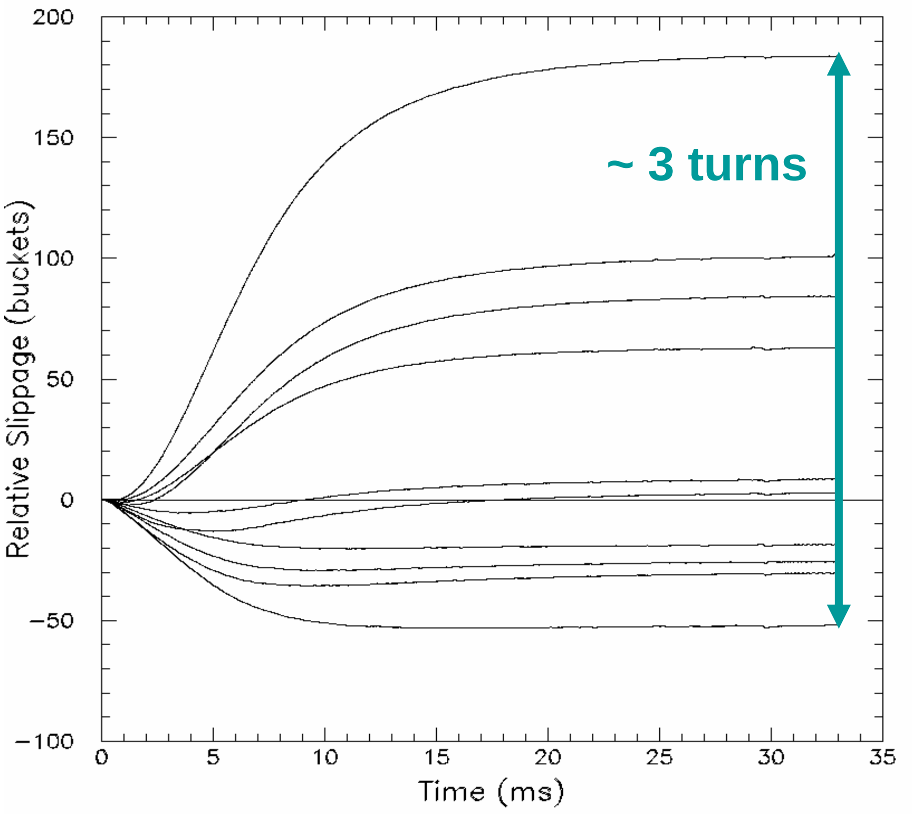
- Pulsed devices drag line current down
  - Particularly, RF & bias supplies
- Lower line current reduces power input to GMPS

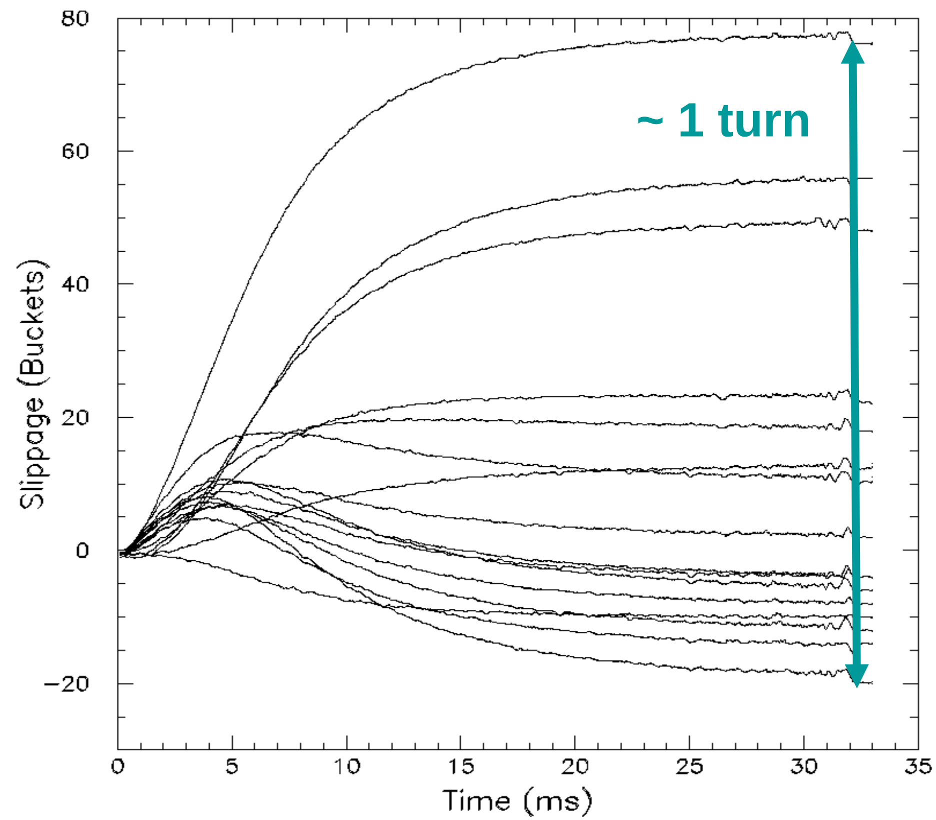
- Apply feedforward correction to GMPS inputs



Error Corrections

w/o correction and w/ correction



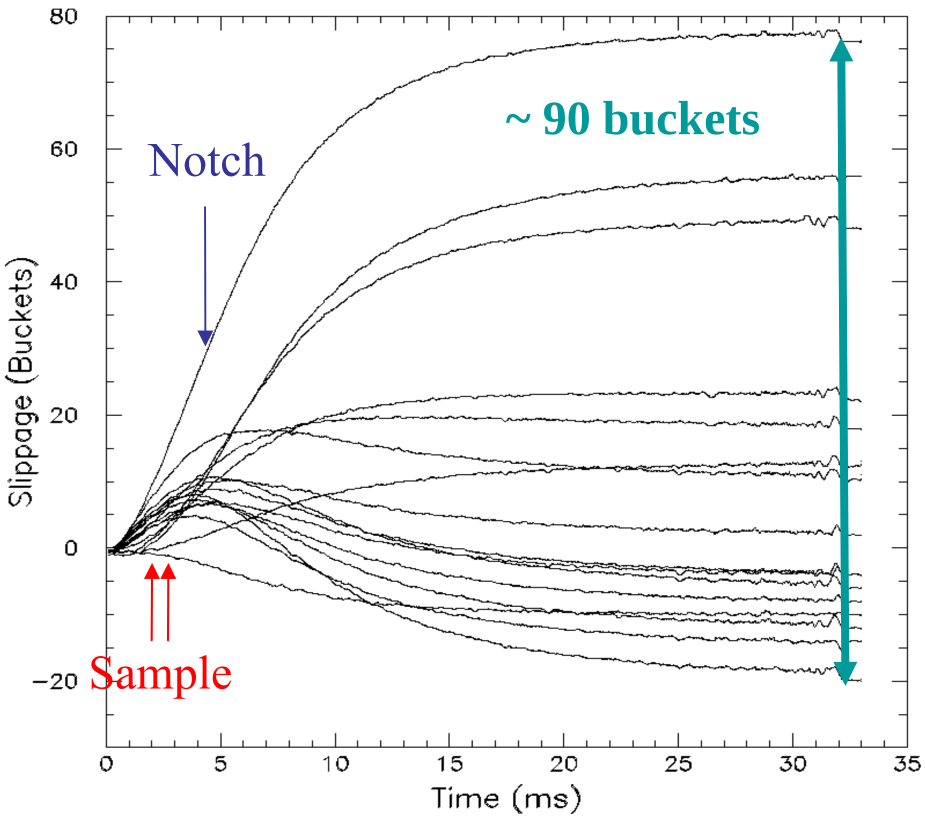


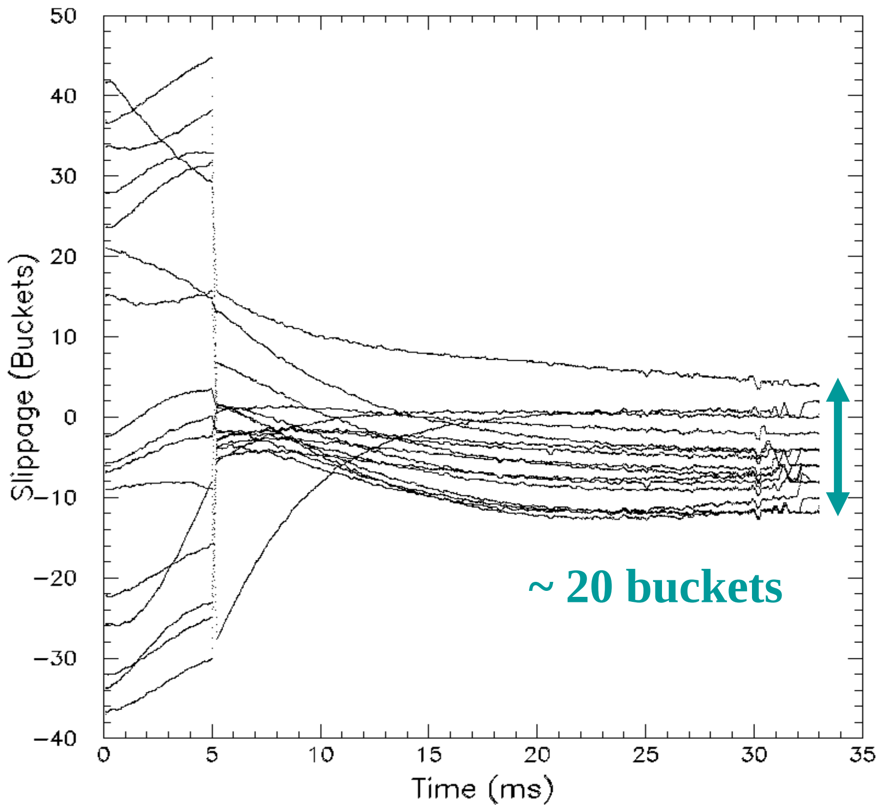
- Also need MI to maintain reference RF frequency

Predictive Notching

- Delay creation of the notch 5 ms
  - Use information of that period
  - Make notch anticipating further slippage.

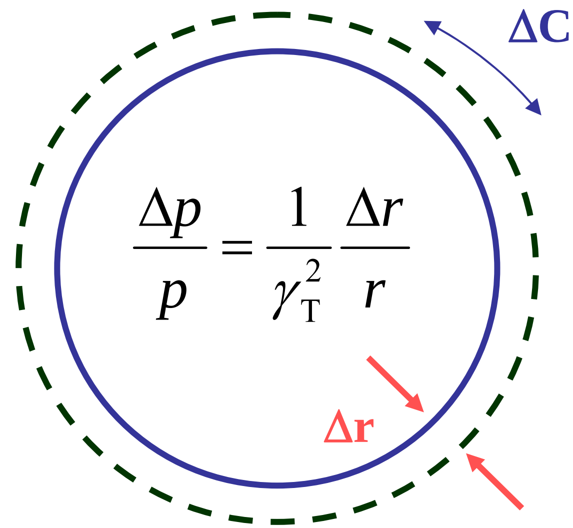
w/o correction and w/ correction

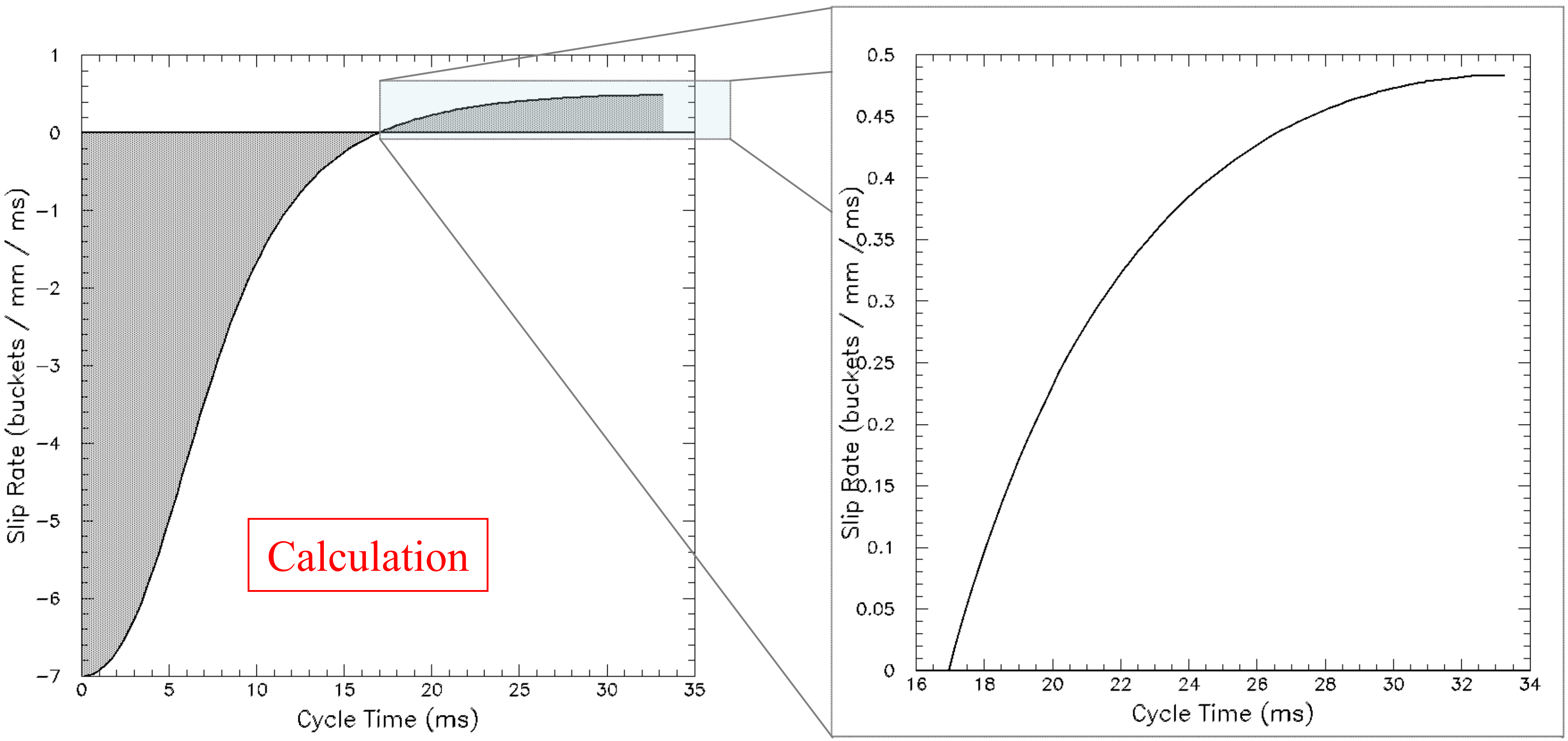




Radially Induced Slippage

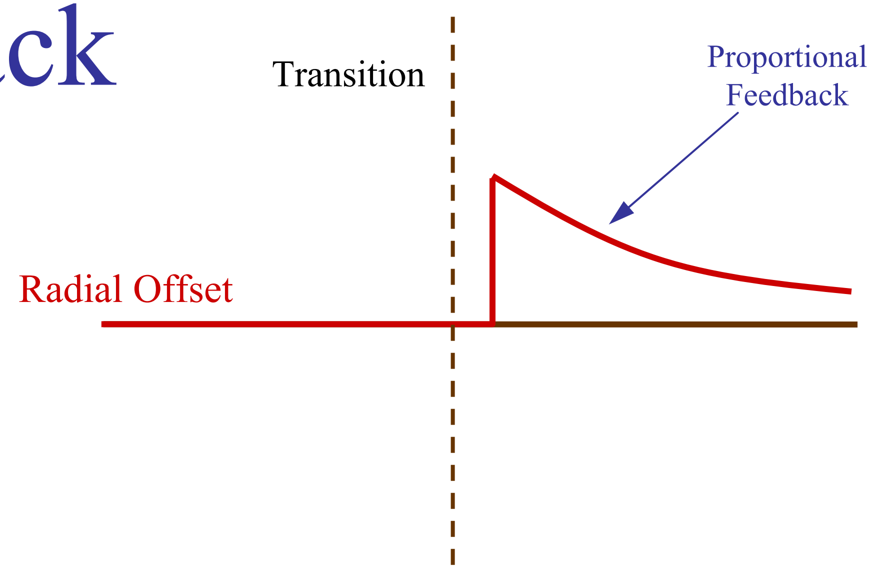
- Induced slippage scales with radial offset
  - Rates of ~ 1 kHz/mm

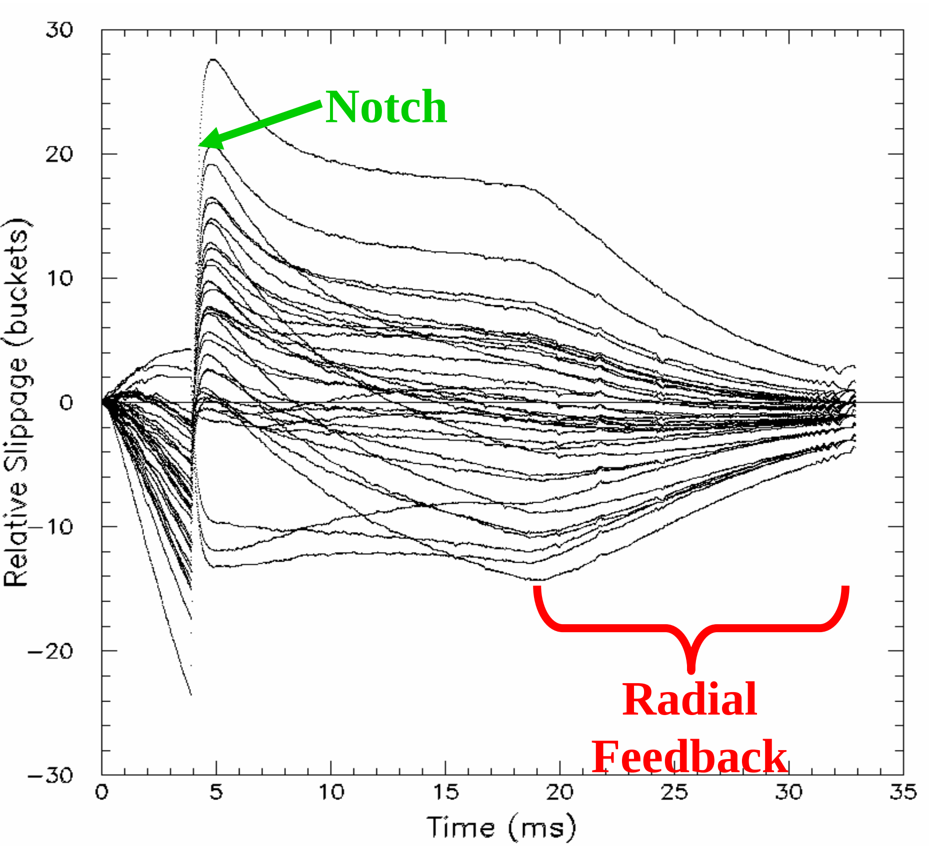


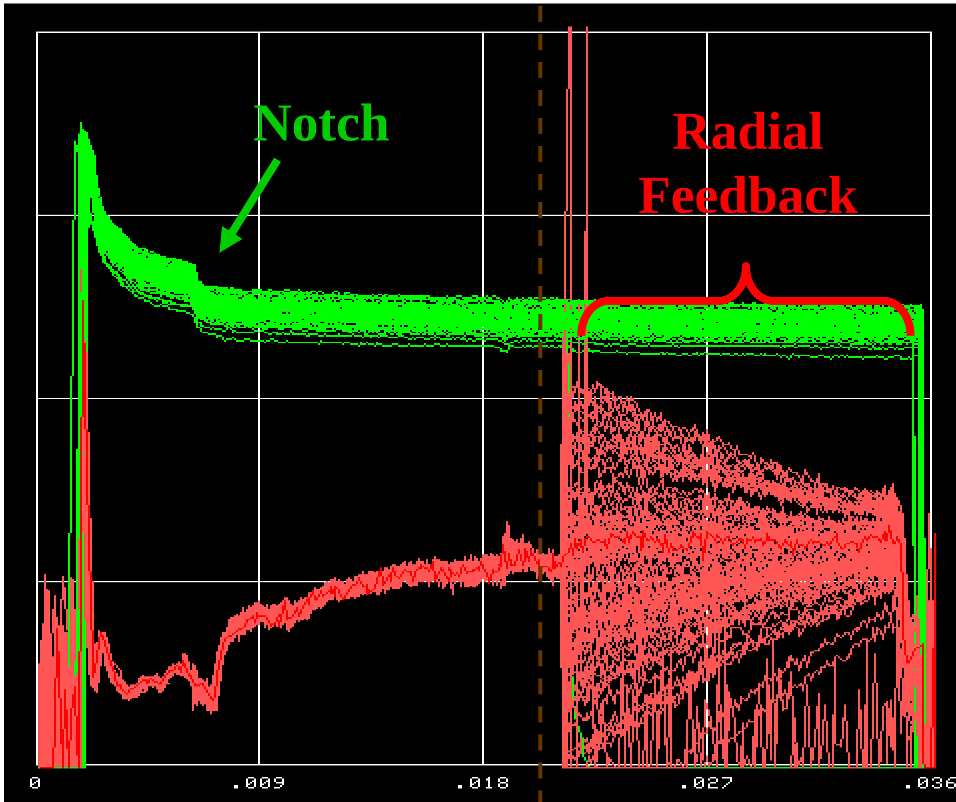


Proportional Feedback

- Notch using prediction
- Radial Feedback late in the cycle
- $\Delta r = k \cdot \Delta S$
  - Exponential damping
  - $k \approx 0.2$ mm / bucket
  - e-folding time $\approx$ 10 ms

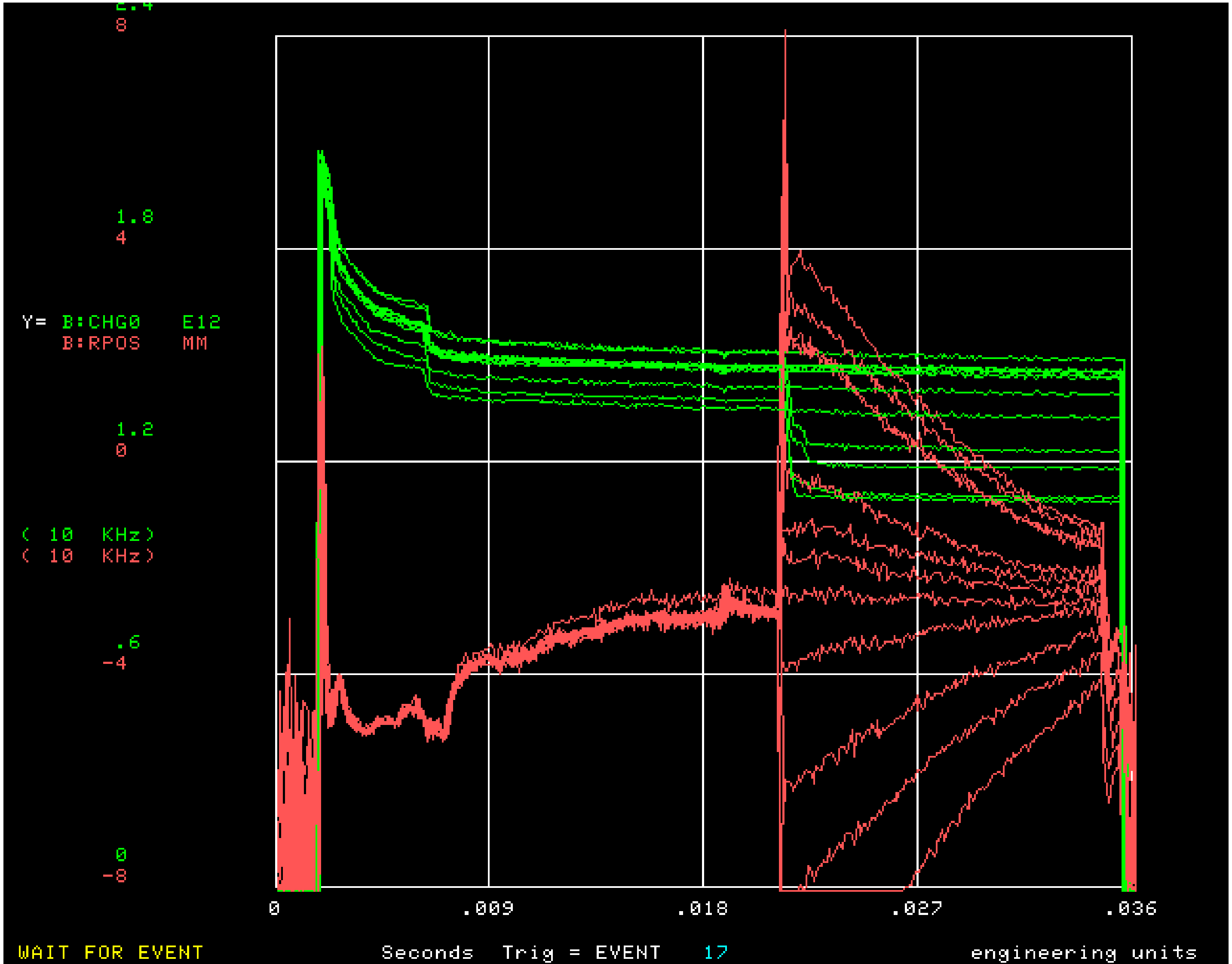






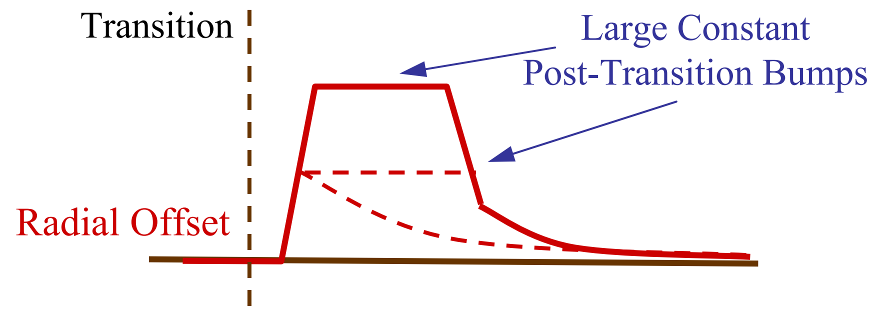
Higher Gain

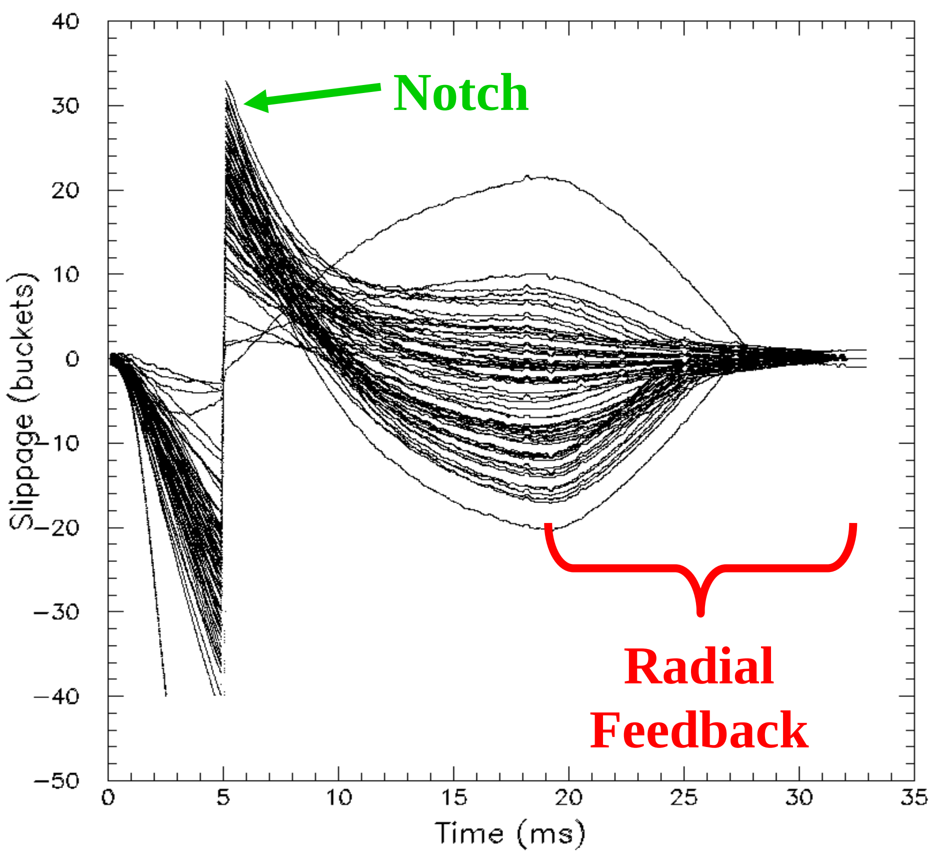
- Causes beam loss

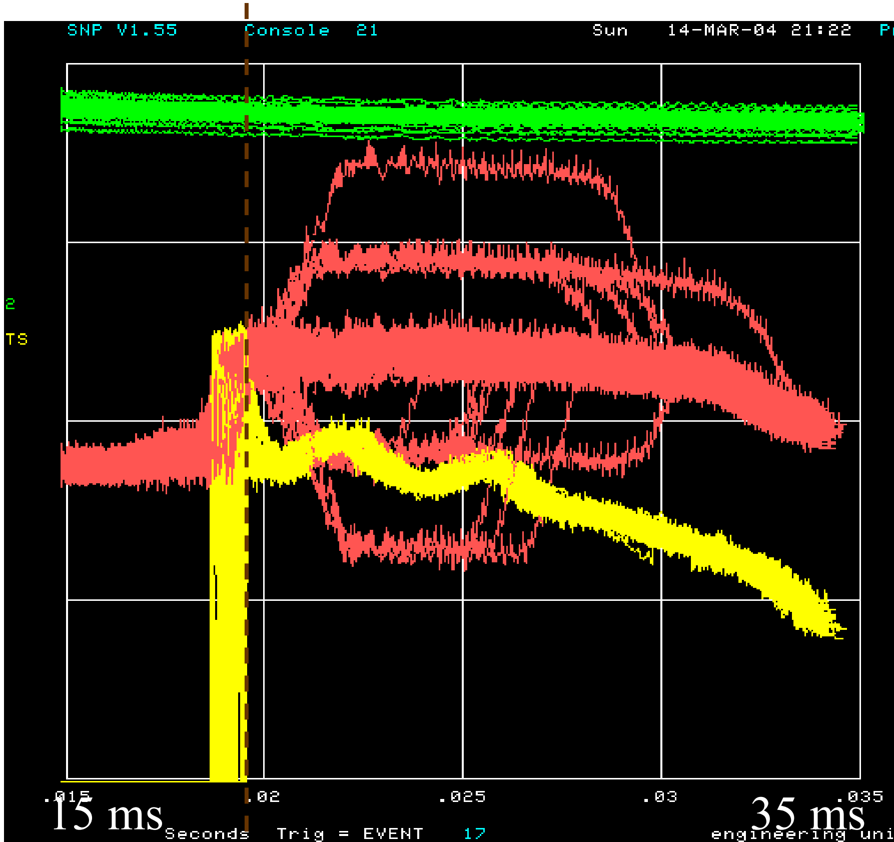


Sustained (Flat) Feedback

- Flat & proportional feedbacks
  - Small error goes to proportional feedback
    - Gigher Gain
  - Larger errors go to a large constant value of feedback
    - Stay there until error is small

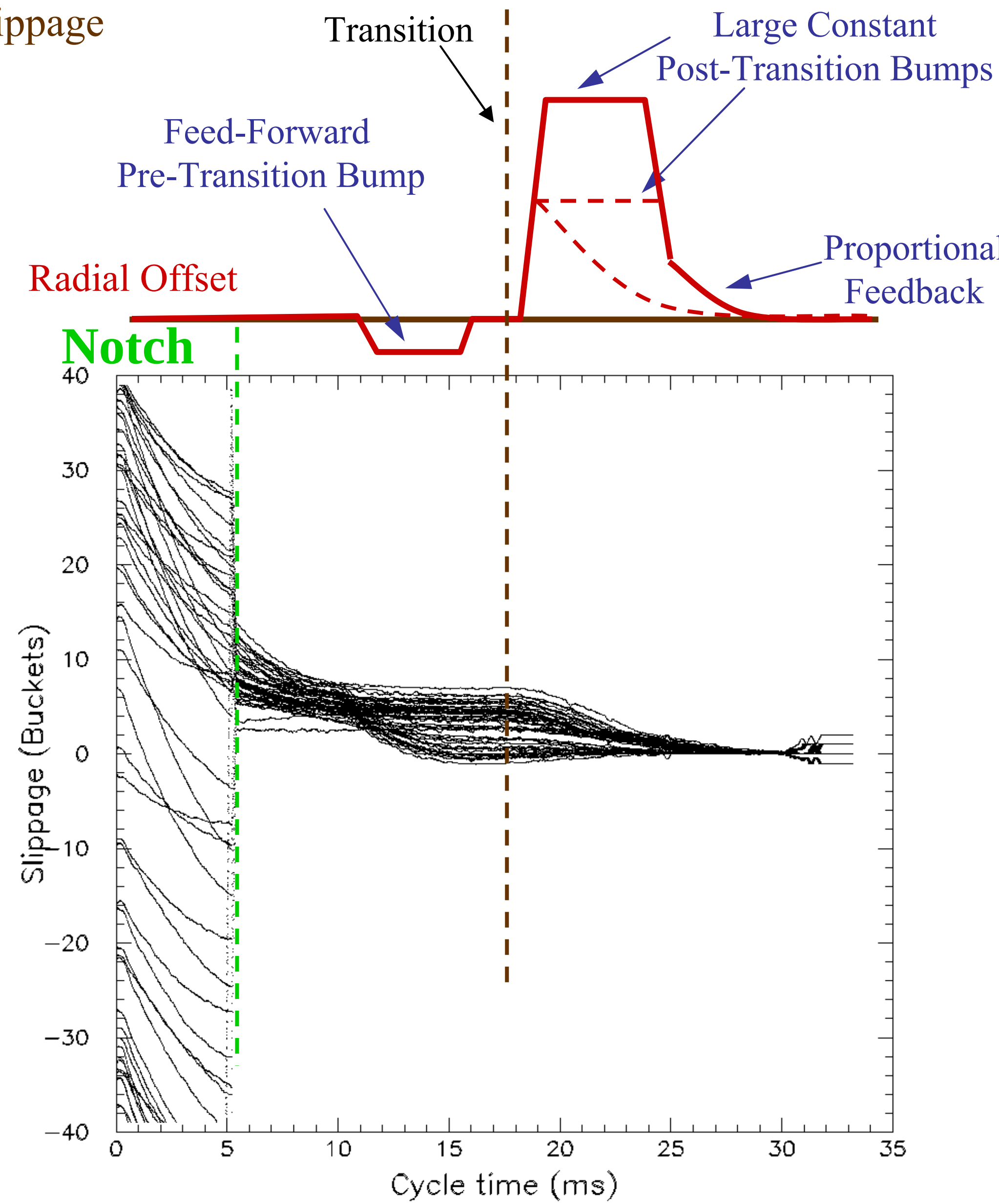






Final Cogging Algoritm

- Notch delayed, and placed in anticipation of slippage
  - ➢ Pre-transition bump
    - Uses a prediction algorithm
    - Reduces post-trans. cogging necessary
  - ➢ Flat feedback is the same as above
  - ➢ Proportional feedback is doubled



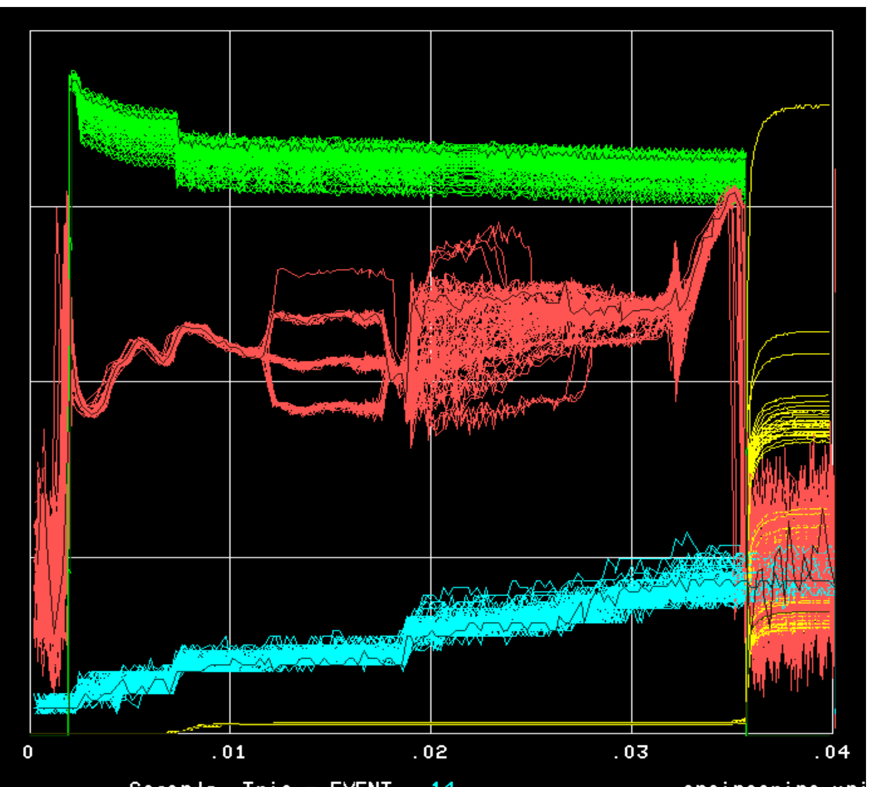
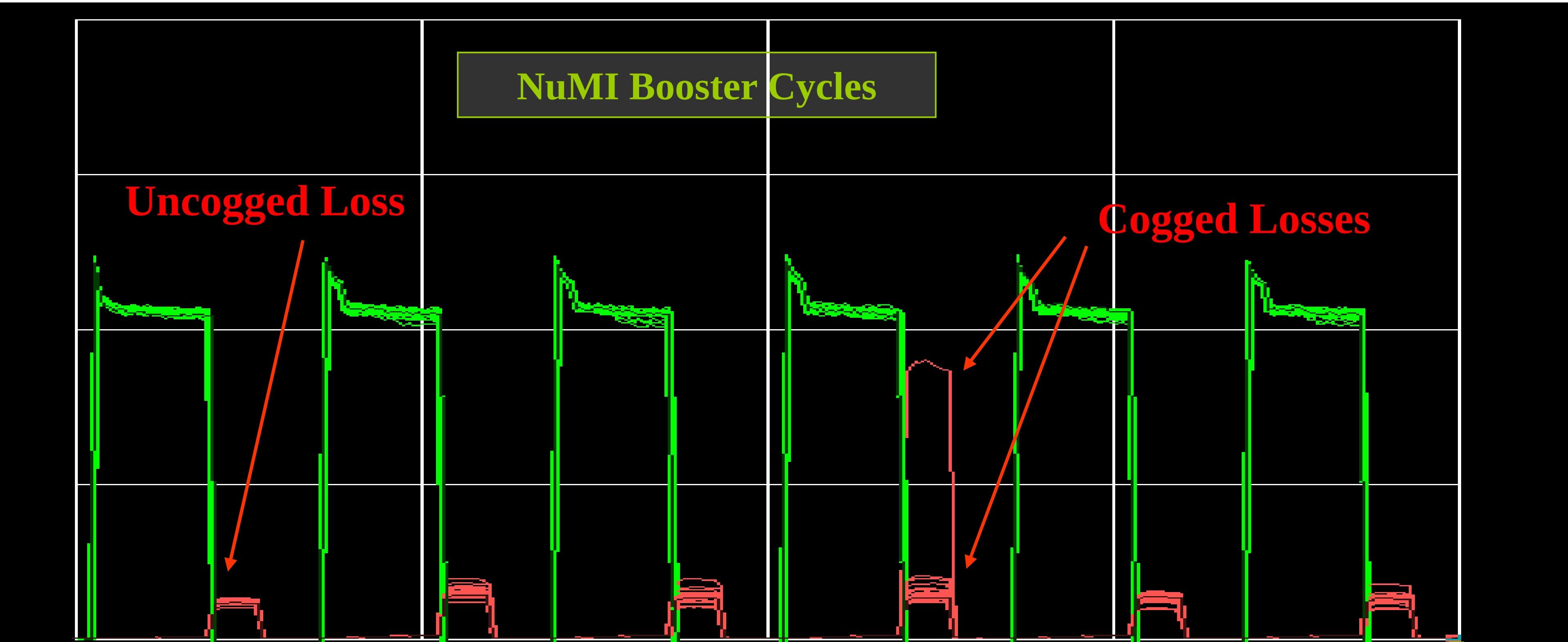


Figure of Merit: Extraction Losses

- Cogging reduces extraction losses substantially
  - 80-90%, depending on conditions
- Occasional misses caused by phaselock or small timing errors
  - Override reduces phaselock losses by pushing error into MI
- Overall – running such that cogging losses rarely limit Booster throughput



Cogging in Balance

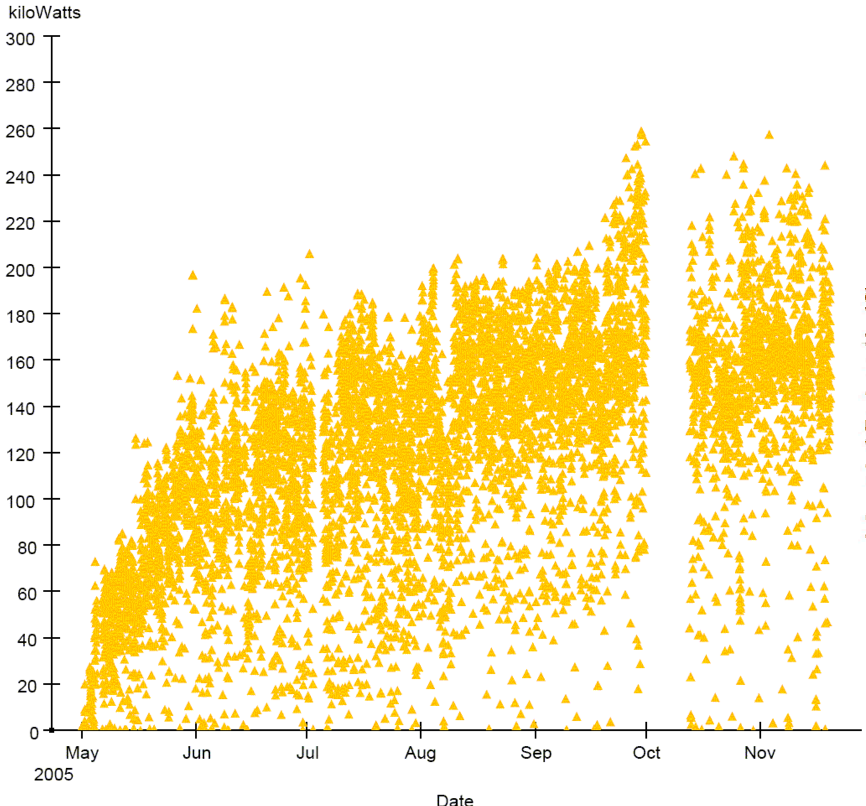
- Cogging effects:
  - Later notch results in more loss
  - Radial motion
    - Before trans: ± 1(2) mm
    - After trans: ± 2(4) mm
  - GMPS must be controlled
  - BDOT signal is vital
  - Phaselock interferes
  - MI is more constrained

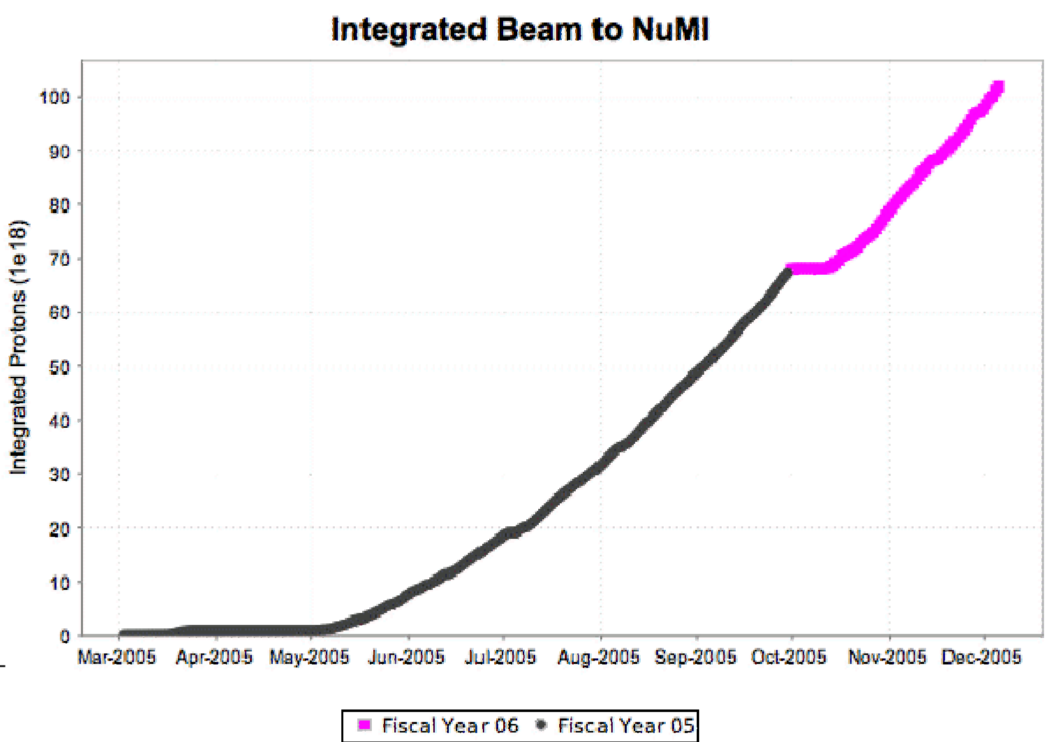
- Hardware running stably
  - Very few glitches
  - Extraction losses reduced 80-90%
- Only method for multibatch
  - Adequate for today's running

- In the future:
  - Only a few tweaks in cogging algorithms are possible
    - Maybe inputs to other ramped systems
  - Higher intensity beam might require smaller range of movement
  - Phaselock can be redesigned
  - Faster kickers?
  - …

Summary: Beam Delivered

- Booster cogging on multibatch cycles for slip-stacking and NuMI
  - ➢ Sources of variation were identified, and eliminated where possible
  - ➢ System to enforce synch by feedback (feedforward)
  - ➢ System made operational ~ 1 yr ago
    - Over 30,000,000 cogged cycles
- Peak proton power to NuMI has approached 300 kW, achieving 10^{20} protons





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